

# Forming of Titanium and Titanium Alloys

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TITANIUM AND ITS ALLOYS can be formed in standard machines to tolerances similar to those obtained in the forming of stainless steel. However, to reduce the effect of springback variation, improve accuracy, and to gain the advantage of increased ductility, the great majority of formed titanium parts are made by hot forming or by cold preforming and then hot sizing.

The following characteristics of titanium and titanium alloy sheet materials must be considered in forming:

- Notch sensitivity, which may cause cracking and tearing, especially in cold forming
- Galling (more severe than with stainless steel)
- Relatively poor ability to shrink (a disadvantage in some flanging operations)
- Potential embrittlement from overheating and from absorption of gases, principally hydrogen and oxygen (scale and the surface layer adversely affected by the slower penetration of oxygen can be removed readily)
- Limited workability—varies with the alloy
- Higher springback than that encountered in ferrous alloys at the same strength level

However, as long as these limitations are recognized and established guidelines for hot and cold forming are followed, titanium and titanium alloys can be successfully formed into complex parts.

The mechanical properties, and therefore the formabilities, of titanium and its alloys vary widely. For example, the tensile strength of different grades of commercially pure (CP) titanium ranges from 240 to 550 MPa (35 to 80 ksi); correspondingly large differences in formability are obtainable at room temperature. The tensile strength and ductility of CP titanium are largely dependent on its oxygen content. Table 1 lists the common designations, compositions, and selected mechanical properties of some titanium alloys.

## Titanium Alloys

**Alloy Ti-6Al-4V** is the most widely used titanium alloy, accounting for approximately 60% of total titanium production. Unalloyed grades constitute approximately 20% of pro-

duction, and all other alloys make up the remaining 20%. Selection of an unalloyed grade of titanium, an  $\alpha$  or near- $\alpha$  alloy, an  $\alpha$ - $\beta$  alloy, or  $\beta$  metastable alloy depends on desired mechanical properties, forming method, service requirements, cost, and the other factors that enter into any materials selection process. The high solubility of the interstitial elements oxygen and nitrogen makes titanium rather unique among metals and creates problems that are not of concern in most other metals. For example, heating titanium in air at high temperature results not only in oxidation but also in solid-solution hardening of the surface as a result of inward diffusion of oxygen. A surface-hardened zone (alpha case) is formed. This layer is usually removed by machining or chemical milling prior to placing a part in service. The presence of this layer reduces fatigue strength and ductility.

**Commercially pure titanium** is usually selected for its excellent corrosion resistance, especially in applications in which high strength is not required. The yield strengths of CP grades (Table 1) vary from less than 170 to more than 480 MPa (25 to 70 ksi) as a result of variation in the interstitial, grain size, and impurity levels. Oxygen and iron are the primary variants in these grades; strength increases with increasing oxygen and iron contents and decreases with grain size. Grades of higher purity (lower interstitial content) are lower in strength, hardness, and transformation temperature than those higher in interstitial content.

**Alpha and Near-Alpha Alloys.** Alpha alloys that contain aluminum, tin, and/or zirconium are preferred for high-temperature and cryogenic applications. Alpha-rich alloys are generally more resistant to creep at high temperature than  $\alpha$ - $\beta$  or metastable  $\beta$  alloys. The extra-low-interstitial  $\alpha$  alloys (ELI grades) retain ductility and toughness at cryogenic temperatures, and Ti-5Al-2.5Sn-ELI has been extensively used in such applications. Unlike  $\alpha$ - $\beta$  and metastable  $\beta$  alloys,  $\alpha$  alloys cannot be strengthened by heat treatment. Generally,  $\alpha$  alloys are annealed or recrystallized to remove residual stresses induced by cold working. Alpha alloys that contain small additions of  $\beta$  stabilizers (for example, Ti-8Al-1V-1Mo or Ti-6Al-2Nb-1Ta-0.8Mo) are sometimes classed as near- $\alpha$  alloys.

Although they contain some retained  $\beta$  phase, these alloys consist primarily of  $\alpha$  and behave more like conventional  $\alpha$  alloys than  $\alpha$ - $\beta$  alloys. They can, however, be strengthened by grain size.

**Alpha-beta alloys** contain one or more  $\alpha$  stabilizers or  $\alpha$ -soluble element plus one or more  $\beta$  stabilizers. These alloys retain more  $\beta$  phase after final heat treatment than near- $\alpha$  alloys; the specific amount depends on the amount of  $\beta$  stabilizers present and on the solution heat treating temperature and time.

Alpha-beta alloys can be strengthened by solution treating and aging. Solution treating is usually done at a temperature high in the two-phase  $\alpha$ - $\beta$  field and is followed by quenching in water, oil, or other suitable quenchant. The  $\beta$  phase present at the solution-treating temperature may be retained or may be partly transformed during cooling by either martensitic transformation or nucleation and growth. The specific response depends on alloy composition, solution-treating temperature ( $\beta$ -phase composition at the solution temperature), cooling rate, and section size. Solution treatment is followed by aging, usually in the 480 to 650 °C (900 to 1200 °F) range.

Solution treating and aging can increase the strength of  $\alpha$ - $\beta$  alloys 20 to 50%, or more, over the annealed or overage condition. Response to solution treating and aging depends on section size; alloys relatively low in stabilizers (Ti-6Al-4V, for example) have poor hardenability and must be quenched rapidly to achieve significant strengthening. For Ti-6Al-4V, the cooling rate of a water quench is not rapid enough to cause significant hardening of sections thicker than approximately 25 mm (1 in.). Hardenability increases as the content of  $\beta$  stabilizers increases. It should be noted that distortion can also be experienced during the solution-treating operation. The thinner the material, the greater the distortion when using water quench. It is best to use sheet material in the annealed condition to eliminate this problem.

**Metastable beta alloys** are richer in  $\beta$ -phase stabilizers and leaner in  $\alpha$  stabilizers than  $\alpha$ - $\beta$  alloys. They are characterized by high hardenability, with  $\beta$  phase completely retained upon the air cooling of thin sections or the water quenching of thick sections. Beta alloys in sheet

**Table 1** Designations, nominal compositions, and selected mechanical properties of selected titanium alloys

ASTM	MIL-T-9046F	MIL-T-9046H	MIL-T-9046J/ AMS-T-9046A	Minimum ultimate tensile strength		Minimum 0.20% yield strength		Elongation, %
				MPa	ksi	MPa	ksi	
Type I: Commercially pure titanium								
ASTM grade 2	Comp. A: Unalloyed (275 MPa, or 40 ksi, yield)	Comp. A: Unalloyed (275 MPa, or 40 ksi, yield)	CP-3	345	50	280–450	40–65	20
ASTM grade 4	Comp. B: Unalloyed (480 MPa, or 70 ksi, yield)	Comp. B: Unalloyed (480 MPa, or 70 ksi, yield)	CP-1	550	80	480–655	70–95	15
ASTM grade 3	Comp. C: Unalloyed (380 MPa, or 55 ksi, yield)	Comp. C: Unalloyed (380 MPa, or 55 ksi, yield)	CP-2	450	65	380–550	55–80	18
ASTM grade 1	...	...	CP-4	240	35	170–310	25–45	24
Type II: Alpha titanium alloy								
...	Comp. A: 5Al-2.5Sn	Comp. A: 5Al-2.5Sn	A-1	790	115	760	110	10
...	Comp. B: 5Al-2.5Sn (ELI)(a)	Comp. B: 5Al-2.5Sn (ELI)(a)	A-2	690	100	657	95	6
...	Comp. F: 8Al-1Mo-1V	Comp. F: 8Al-1Mo-1V	A-4	828	120	760	110	6
...	Comp. GT: 6Al-2Cb-1Ta-0.8Mo	Comp. GT: 6Al-2Cb-1Ta-0.8Mo	A-3	711	103	657	95	10
Type III: Alpha-beta titanium								
...	Comp. A: 8Mn	...	AB-6	863	125	761	110	10
ASTM grade 5	Comp. C: 6Al-4V	Comp. C: 6Al-4V	AB-1	897	130	830	120	8
...	Comp. D: 6Al-4V (ELI)(a)	Comp. D: 6Al-4V (ELI)(a)	AB-2	863	125	934	135	6
...	Comp. E: 6Al-6V-2Sn	Comp. E: 6Al-6V-2Sn	AB-3	1001	145	934	135	8
...	Comp. G: 6Al-2Sn-4Zr-2Mo	Comp. G: 6Al-2Sn-4Zr-2Mo	AB-4	897	130	830	120	8
...	...	Comp. H: 6Al-4V-SPL	AB-5	621	90	519	75	15
Type IV: Beta titanium								
...	Comp. A: 13V-11Cr-3Al	Comp. A: 13V-11Cr-3Al	B-1	911	132	872	126	8
...	...	Comp. B: 11.5Mo-6Zr-4.5Sn	B-2	690	100	623	90	10
...	...	Comp. C: 3Al-8V-6Cr-4Mo-4Zr	B-3	828	120	796	115	6
...	...	Comp. D: 8Mo-8V-2Fe-3Al	B-4	828	120	796	115	8
Ti-15V-3Al-3Cr-3Sn	...	...	...	790	115	770	112	20–25
(a) ELI, extra-low interstitial								

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form can be cold formed more readily than high-strength  $\alpha$ - $\beta$  or  $\alpha$  alloys. An example of this is the Ti-15V-3Sn-3Cr-3Al alloy, which is formed almost exclusively at room temperature. After solution treating, metastable  $\beta$  alloys are aged at temperatures of 450 to 650 °C (850 to 1200 °F) to partially transform the  $\beta$  phase to  $\alpha$ . The  $\alpha$  forms as finely dispersed particles in the retained  $\beta$  and gives strength levels comparable to or superior to those of aged  $\alpha$ - $\beta$  alloys.

In the solution-treated condition (100% retained  $\beta$ ), metastable  $\beta$  alloys have good ductility and toughness, relatively low strength, and excellent uniaxial formability. However, their formability is less for biaxial forming. Solution-treated metastable  $\beta$  alloys begin to precipitate  $\alpha$  phase at slightly elevated temperatures and are therefore generally unsuitable for elevated-temperature service without prior stabilization or overaging treatment.

## Superplastic Alloys

The workhorse superplastic titanium alloy is Ti-6Al-4V, and the state-of-the-art in titanium superplastic forming is largely based on this alloy. However, a number of titanium alloys, especially the  $\alpha$ - $\beta$  alloys, exhibit superplastic behavior. Many of these materials, such as Ti-6Al-4V, are superplastic without special processing. Table 2 gives data concerning the superplastic behavior of some titanium alloys and lists the characteristics used to describe

**Table 2** Superplastic characteristics of titanium alloys

Alloy	Test temperature		Strain rate, s <sup>-1</sup>	Strain-rate sensitivity factor, <i>m</i>	Elongation, %
	°C	°F			
Commercially pure titanium	850	1560	$17 \times 10^{-4}$	...	115
<b><math>\alpha</math>-<math>\beta</math> alloys</b>					
Ti-6Al-4V	840–870	1545–1600	$1.3 \times 10^{-4}$ to $10^{-3}$	0.75	750–1170
Ti-6Al-5V	850	1560	$8 \times 10^{-4}$	0.70	700–1100
Ti-6Al-2Sn-4Zr-2Mo	900	1650	$2 \times 10^{-4}$	0.67	538
Ti-4.5Al-5Mo-1.5Cr	870	1600	$2 \times 10^{-4}$	0.63–0.81	>510
Ti-6Al-4V-2Ni	815	1500	$2 \times 10^{-4}$	0.85	720
Ti-6Al-4V-2Co	815	1500	$2 \times 10^{-4}$	0.53	670
Ti-6Al-4V-2Fe	815	1500	$2 \times 10^{-4}$	0.54	650
Ti-5Al-2.5Sn	1000	1830	$2 \times 10^{-4}$	0.49	420
<b>Near-<math>\beta</math> and <math>\beta</math> alloys</b>					
Ti-15V-3Sn-3Cr-3Al	815	1500	$2 \times 10^{-4}$	0.50	229
Ti-13Cr-11V-3Al	800	1470	...	...	<150
Ti-8Mn	750	1380	...	0.43	150
Ti-15Mo	800	1470	...	0.60	100

Source: Ref 1

superplastic properties in engineering alloys: strain-rate sensitivity factor, *m*, and tensile elongation. The *m*-value is a measure of the rate of change of flow stress with strain rate; the higher the *m* value of an alloy, the greater its superplasticity. Titanium alloys that have exhibited superplasticity but are not listed in Table 2 include Ti-3Al-2.5V (ASTM grade 9), Ti-4.5Al-1.5Cr-5Mo (Corona 5), and Ti-0.3Mo-0.8Ni (ASTM grade 12).

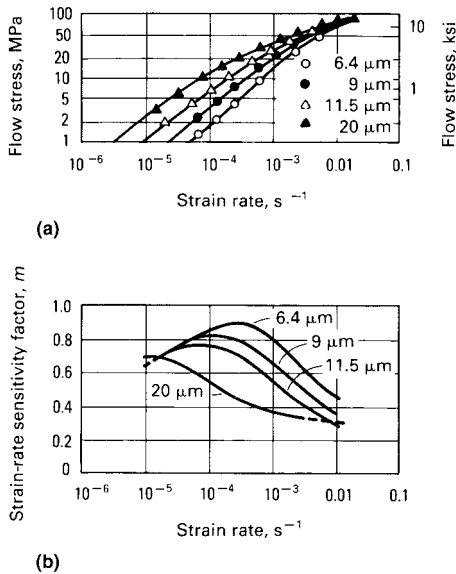
Metallurgical variables that affect superplastic behavior in titanium alloys include grain size, grain size distribution, grain growth kinetics,

diffusivity, phase ratio in  $\alpha$ - $\beta$  alloys, and texture (Ref 1). Alloy composition is also significant, because it has a pronounced effect on  $\alpha$ - $\beta$  phase ratio and on diffusivity.

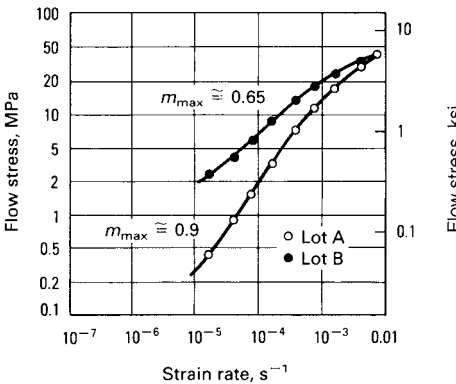
Grain size is known to have a strong influence on the superplastic behavior of Ti-6Al-4V (Ref 2, 3). This is illustrated in Fig. 1, which shows flow stress and strain-rate sensitivity factor, *m*, as a function of strain rate for Ti-6Al-4V materials with four different grain sizes. Increasing grain size increases the flow stress, reduces maximum *m*-value, and reduces the strain rate at which maximum *m* is observed.

**Grain Size Distribution.** Figure 2 shows flow stress versus strain rate for Ti-6Al-4V alloys with two different grain size ranges. The material with the smaller grain size distribution (lot A) exhibits significantly lower flow stresses than the material with the larger grain size distribution (lot B). Maximum *m*-value is also higher for the lot A material.

Grain growth kinetics affect superplastic behavior in direct relation to the grain size developed in the material. A study of grain growth effects on Ti-6Al-4V found that the flow hardening observed during constant strain-rate superplastic flow was the direct result of grain growth (Ref 3). It was also observed that grain growth accelerated with increasing strain rate. This grain growth causes an increase in flow stress and a decrease in maximum *m*-value.



**Fig. 1** (a) Flow stress and (b) strain-rate sensitivity factor, *m*, versus strain rate for Ti-6Al-4V materials with four different grain sizes. Test temperature: 927 °C (1700 °F). Source: Ref 3



**Fig. 2** Effect of grain size distribution on flow stress versus strain-rate data for Ti-6Al-4V at 927 °C (1700 °F). Lot A, average grain size of 4 μm and grain size range of 1 to 10 μm; lot B, average grain size of 4.6 μm but grain size range of 1 to >20 μm. Source: Ref 4

Diffusivity is an important quantity in the superplastic flow of titanium alloys (and other engineering materials). The best indicator of diffusivity is usually activation energy, *Q*, which can be determined from the change in strain rate with temperature (Ref 1). Values of *Q* have been determined for several titanium alloys and for the α and β phases of titanium alloys. As indicated in Table 3, the activation energies determined from superplastic data are consistently higher than those for self-diffusion. It has been suggested that the higher *Q* values seen in superplastic alloys are due to the fact that the volume fraction of β phase in the alloys investigated increases with temperature, exaggerating the strain-rate increase and resulting in falsely high *Q* values. This complicates efforts to establish specific deformation mechanisms.

**Phase Ratio Effects.** Figure 3 shows that the two-phase (α-β) titanium alloys seem to exhibit greater superplasticity than other titanium alloys. The α and β phases are quite different in terms of crystal structure (hexagonal close-packed for α, and body-centered cubic for β) and diffusion kinetics. Beta phase exhibits a diffusivity approximately 2 orders of magnitude greater than that of α phase. For this reason alone it should be expected that the amount of β phase present in a titanium alloy would have an effect on superplastic behavior.

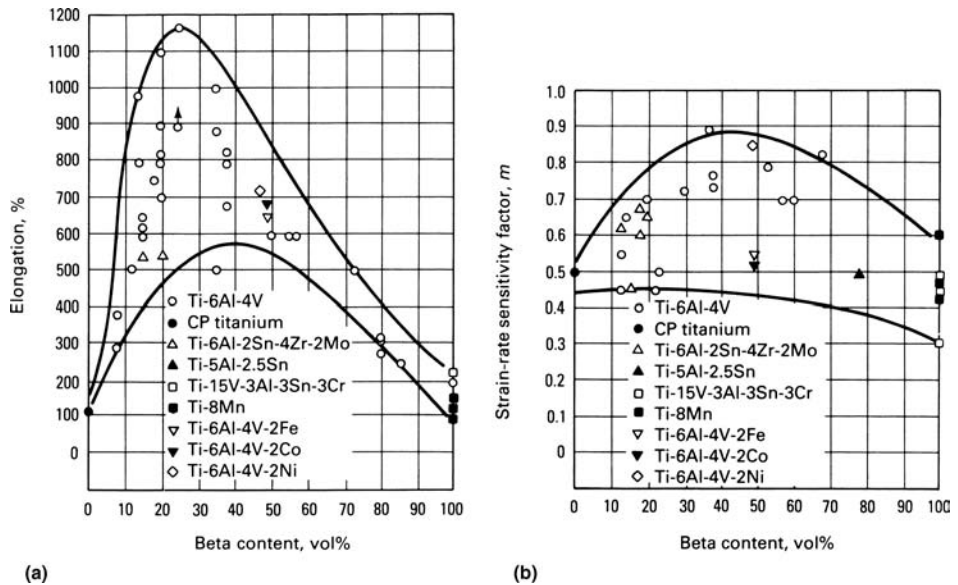
Figure 3 shows elongations and *m*-values for several titanium alloys as a function of the volume fraction of β phase present in the alloys. It can be readily seen that elongation values reach a peak at approximately 20 to 30 vol% β phase (Fig. 3a), while *m*-values peak at β contents of approximately 40 to 50 vol% (Fig. 3b). Because *m* is usually considered to be a good indicator of superplasticity, this discrepancy in the location of maximal of the curves in Fig. 3 may be surprising. It is believed that the difference stems from a grain growth effect during superplastic deformation. Beta phase is known to exhibit more rapid grain coarsening than α, and the maximum ductility may be the result of a balance between moderated grain growth (due to the presence of α phase) and enhanced diffusivity (due to the presence of β).

General Formability

Titanium metals exhibit a high degree of springback in cold forming. To overcome this characteristic, titanium must be extensively overformed or hot sized after cold forming. Aging or stress-relief operations are usually conducted on titanium alloys that are cold formed. Straightening can be done during the aging or stress-relief cycle with proper tools.

**Table 3** Activation energies for superplastic deformation and self-diffusion in titanium alloys

Alloy	Temperature range		Activation energy ( <i>Q</i> ), kcal/mol	Ref
	°C	°F		
Ti-5Al-2.5Sn	800–950	1470–1740	50–65	2
Ti-6Al-4V	800–950	1470–1740	45	5
Ti-6Al-4V	850–910	1560–1670	45–99	6
Ti-6Al-4V	815–927	1500–1700	45–52	7
Ti-6Al-2Sn-4Zr-2Mo	843–900	1550–1650	38–58	8
Self-diffusion, α phase	...	...	40.4	9
Self-diffusion, β phase	...	...	36.5	10
Self-diffusion, β phase	...	...	31.3	11



**Fig. 3** (a) Elongation and (b) *m*-value as a function of β-phase content for several titanium alloys

Hot forming does not greatly affect final properties. Forming at temperatures ranging from 595 to 815 °C (1100 to 1500 °F) allows the material to deform more readily and simultaneously stress relieves the deformed material; it also minimizes springback. The net effect in any forming operation depends on total deformation and actual temperature during forming. Because titanium metals tend to creep at elevated temperature, holding under load at the forming temperature (creep forming) is another alternative for achieving the desired shape without the need to compensate for extensive springback.

**The Bauschinger Effect.** In all forming operations, titanium and its alloys are susceptible to the Bauschinger effect, which is a drop in compressive yield strength subsequent to tensile straining and vice versa. The Bauschinger effect, unlike the strain-hardening behavior observed in other metals, involves stress-strain asymmetry that results in hysteretic stress-strain loops such as those shown schematically in Fig. 4. The Bauschinger effect is most pronounced at room temperature; plastic deformation (1 to 5% tensile elongation) at room temperature always introduces a significant loss in compressive yield strength, regardless of the initial heat treatment or strength of the alloys. At 2% tensile strain, for example, the compressive yield strength of Ti-6Al-4V drops to less than one-half the value for solution-treated material. Increasing the temperature reduces the Bauschinger effect; subsequent full thermal stress relieving completely removes it.

The Bauschinger effect can be removed at temperatures as low as the aging temperature in

solution-treated titanium alloys. Heating or plastic deformation at temperatures above the normal aging temperature for solution-treated Ti-6Al-4V will cause overaging; as a result, all mechanical properties will decrease.

## Sheet Preparation

Before titanium sheet is formed, it should be inspected for flatness, uniformity, and thickness. Some manufacturers test incoming material for hardness, strength, and bending behavior.

Critical regions of titanium sheet should not be nicked, scratched, or marred by tool or grinding marks, because the metal is notch sensitive. All scratches deeper than the finish produced by 180-grit emery should be removed by sanding the surface. Edges of the workpieces should be smooth, and scratches, if any, should be parallel to the edge of the blank to prevent stress concentration that could cause the workpiece to break. To aid in forming, surface oxide or scale should be removed before forming.

**Cleaning.** Grease, oil, stencils, fingerprints, dirt, and all chemicals or residues that contain halogen compounds must be removed from titanium before any heating operation. Salt residues on the surface of the workpiece can cause hot-salt cracking in service or in heat treating; even the salt from a fingerprint can cause problems. Therefore, titanium is often handled with clean cotton gloves after cleaning and before hot forming, hot sizing, or heat treatment.

Ordinary cleaners and solvents such as isopropyl alcohol and acetone are used on titanium. Halogen compounds, such as trichlorethylene, should not be used, unless the titanium is pickled in acid after cleaning.

Titanium that has been straightened or formed with tools made of lead or low-melting alloy should be cleaned in nitric acid. Detailed information on the cleaning of titanium is given in the article "Surface Engineering of Titanium and Titanium Alloys" in *Surface Engineering*, Volume 5 of *ASM Handbook*, 1994.

Grinding the sheet to final thickness leaves marks in titanium that can be moderated in an aqueous acid bath containing (by volume) 30% concentrated nitric acid and not more than 3% hydrofluoric acid. Failure to keep the ratio of nitric to hydrofluoric acid at 10 to 1 or greater (to suppress the formation of hydrogen gas during pickling), or the use of any pickling bath that produces hydrogen, can result in excessive hydrogen pickup. The acid bath should remove 0.025 to 0.075 mm (0.001 to 0.003 in.) of thickness from each surface to eliminate the marks made by abrasives. Titanium should be washed or cleaned before it is immersed in acid. The material left on the surface may protect the surface from the acid.

After thermal exposure, thin oxides that form at temperatures below 540 °C (1000 °F) can be removed by acid pickling. Very tenacious oxides may require grit blasting prior to pickling.

Exposure above 540 °C (1000 °F) forms an oxygen-rich surface layer on titanium. This surface is made up of a scale and an alpha case layer. The scale is normally reduced by the use of scale-inhibiting coatings put on prior to the thermal exposure. Scale can also be removed by abrasive blasting; however, this may cause distortion in thin parts. The removal of this scale prior to metal removal in the cleaning process improves the surface appearance. The alpha case layer is a brittle layer that must be removed to restore the base metal properties. Chemical milling, machining, or other similar methods accomplish the surface removal. Another method of limiting the formation of the oxygen-rich surface layer is to use a protective atmosphere or vacuum. Argon gas is a commonly used atmosphere for superplastic forming. Argon is applied to one side, with the other being exposed to air. This can cause an alpha case thickness difference from one side to the other.

## Trimming

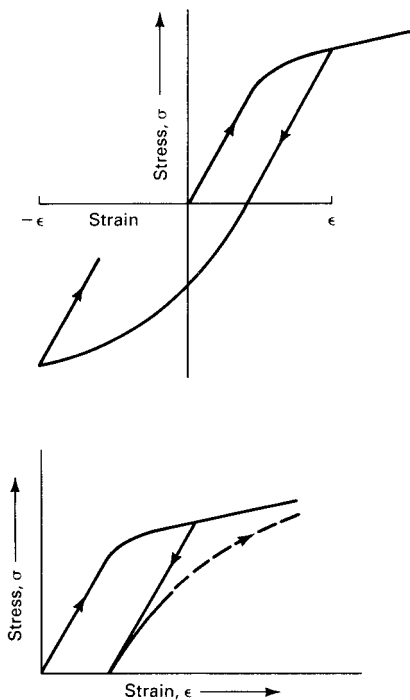
Blanking of titanium alloy sheet and plate 6.4 mm (0.25 in.) thick or less is done in a punch press. As with other metals, maximum blank size depends on stock thickness, shear strength, and available press capacity. Dies must be rigid and sharp to prevent cracking of the work metal. Hardened tool steel must be used for adequate die life.

In one application, holes 6.4 mm (0.25 in.) in diameter were punched in 1.02 to 3.56 mm (0.040 to 0.140 in.) thick annealed alloy Ti-6Al-4V sheet to within  $\pm 0.051$  mm ( $\pm 0.002$  in.) of diameter and with surface roughness of less than 1.3 mm (0.05 in.). The best holes were produced with flat-point punches having 0.025 mm (0.001 in.) die clearance.

Shearing of titanium sheet up to 3.56 mm (0.140 in.) thick can generally be done without difficulty; with extra care, titanium sheet as thick as 6.0 mm (0.25 in.) can be sheared. Shears intended for low-carbon steel may not have enough holddown force to prevent titanium sheets from slipping. A sharp shear blade in good condition with a capacity for cutting 4.8 mm (0.188 in.) thick low-carbon steel can cut 3.2 mm (0.125 in.) thick titanium sheet. Cutters should be kept sharp to prevent edge cracking of the blank.

Sheared edges, especially on thicker sheet metal, can have straightness deviations of 0.25 to 5 mm (0.01 to 0.20 in.), usually because the shear blade is not stiff enough. Shearing can cause cracks at the edges of some titanium sheet thicker than 2.0 mm (0.080 in.). If cracks or other irregularities develop in a critical portion of the workpiece, an alternative method of cutting should be used, such as band sawing, abrasive waterjet cutting, or laser cutting (see the articles "Abrasive Waterjet Cutting" and "Laser Cutting" in this Volume).

Slitting of titanium alloy sheet can be done with conventional slitting equipment and with



**Fig. 4** Schematics showing two types of hysteresis stress-strain loops resulting from the Bauschinger effect in titanium alloys. Source: Ref 12

draw-bench equipment. Slitting shears are capable of straight cuts only; rotary shears can cut gentle contours (minimum radii: ~250 mm, or 10 in.). The process can be used for sheet thickness to 2.54 mm (0.100 in.).

Band sawing prevents cracking at the edges of titanium sheet but causes large burrs. This is usually followed by an edge-sanding operation to remove burrs.

Nibbling can be used to cut irregular blanks of titanium, but most blanks need filing or sanding after nibbling to produce a uniform edge.

All visual evidence of a sheared or broken edge on a part should be removed by machining, sanding, or filing before final deburring or polishing. All rough projections, scratches, and nicks must be removed. Extra material must be allowed at the edges of titanium blanks so that shear cracks and other defects can be removed. On sheared parts, a minimum of 0.25 mm (0.010 in.) must be removed from the edge; on punched holes, 0.35 mm (0.014 in.). On parts cut by friction band sawing or abrasive sawing, 6.35 mm (0.25 in.) or one thickness of sheet should be removed, whichever is the smaller.

The lay of the finish on the edges of sheet metal parts should be parallel to the edge surface of the blank, and sharp edges should be removed. Edges of shrink flanges and stretch flanges must be polished before forming. To prevent scratching the forming dies, edges of holes and cutouts should be deburred on both sides and should be polished where they are likely to stretch during forming.

## Tool Materials and Lubricants

**Tool materials** for forming titanium are chosen to suit the forming operation, forming temperature, and expected quantity of production. The cost of tool material is generally a small fraction of the cost of tools, unless forming temperature is such that heat-resistant alloy tooling is required. Cold forming can be done with epoxy-faced aluminum, steel, or zinc tools. Hot forming tools are fabricated from ceramic, cast iron, tool steel, stainless steel, and nickel-base alloys. Materials selection is based on the service temperature, hardness of the material and tool at the forming temperature, and the number of parts being formed. Tool steel does not work well when temperatures are above the tempering temperature of the steel or above the temperatures where oxides form on the tool.

Titanium alloys are often formed in heated dies and presses that have a slow, controlled motion and that can dwell in the position needed during the press cycle. Hot forming is sometimes done in dies that include heating elements or in dies that are heated by the press platens. Press platens heated to 650 °C (1200 °F) can transmit enough heat to keep the working faces of the die at 425 to 480 °C (800 to 900 °F). Other methods of heating include electrical-resistance heating and the use of quartz lamps and portable furnaces.

Tool materials for the superplastic forming of titanium alloys are a special case (see the section “Superplastic Forming” in this article). They must be able to withstand the high temperatures (870 to 925 °C, or 1600 to 1700 °F) required for superplastic forming. Cast ceramics, 22-4-9 stainless steel (Fe-0.5C-22Cr-9Mn-4Ni), and 49M steel are used for this purpose. Figure 5 shows a typical tool used at elevated temperatures, in the 870 to 925 °C (1600 to 1700 °F) range. The heavy scale and oxide layer is due to the long exposure at elevated temperatures. Dies are usually cleaned between production runs to keep the surface smooth and ensure an acceptable finish on the parts.

**Lubricants.** Galling is the most severe problem to be overcome in hot forming. Lubricants may react unfavorably with titanium when it is heated, although molybdenum disulfide suspended in a volatile carrier, colloidal graphite, and graphite-molybdenum disulfide mixtures have been successfully used. Boron nitride slurries also are used. If the lubricant reacts with oxidation products to produce a tenacious surface coating, it must be removed by sandblasting with garnet grit or 120-mesh aluminum oxide, followed by acid pickling. Parts can be preformed cold and hot sized to minimize the

galling effects seen in hot forming parts; however, this is not always practical.

Boron nitride is the preferred temperature-resistant lubricant because of its higher lubricity, as well as ease of application and removal. Other lubricants used for hot forming have a graphite, molybdenum disulfide, or  $Y_2O_3$  base.

Lubricants for the cold forming of titanium are generally similar to those used for the severe forming of aluminum alloys (see the articles “Forming of Aluminum Alloys” and “Selection and Use of Lubricants in Forming of Sheet Metal” in this Volume). Tool materials and lubricants for the cold and hot forming of titanium alloys are given in Table 4.

## Cold Forming

Commercially pure titanium and the most ductile metastable  $\beta$  titanium alloys, such as Ti-15V-3Sn-3Cr-3Al and Ti-3Al-8V-6Cr-4Zr-4Mo, can be formed cold to a limited extent. Alloy Ti-8Al-1Mo-1V sheet can be cold formed to shallow shapes by standard methods, but the bends must be of larger radii than in hot forming and must have shallower stretch flanges. The cold forming of other alloys generally results in



**Fig. 5** Typical tool finish after being exposed to elevated temperatures. This hot forming die has a heavy scale and oxide layer caused by long exposure to high temperatures. Dies must be cleaned using abrasives in between production runs in order to avoid mark-off being transferred to the part surface. The light area is alpha case that has been migrated to the die from the titanium parts.

excessive springback, requires stress relieving between operations, and requires more power.

Titanium and titanium alloys are commonly stretch formed without being heated, although the die is sometimes warmed to 150 °C (300 °F). For the cold forming of all titanium alloys, formability is best at low forming speeds.

Hot sizing and stress relieving are ordinarily needed to improve part contour, reduce stress, and avoid delayed cracking and stress corrosion. Stress relief is also needed to restore compressive yield strength after cold forming. Hot sizing is often combined with stress relieving, by holding the workpiece in fixtures or form dies to prevent distortion. Stress-relief treatments for CP titanium and some titanium alloys are given

in Table 5. Hot sizing for shorter times than reflected in the table will remove the springback on some materials. This would indicate that shorter times may be acceptable. Detailed information on the heat treatment of titanium alloys is available in the article “Heat Treating of Titanium and Titanium Alloys” in *Heat Treating*, Volume 4 of *ASM Handbook*, 1991.

The only true cold-formable titanium alloy is Ti-15V-3Sn-3Cr-3Al. Hot sizing is usually not used for this alloy; however, properties must be developed with an aging treatment (8 h at 540 °C, or 1000 °F, is typical). Because of the high springback rates encountered with this alloy, more elaborate tooling must be used. Hot sizing can be used at the solution-treatment

temperature, followed by air cooling. This helps to solve the springback problems seen during the aging process. A restraint fixture can also be used to straighten during aging.

## Hot Forming

Heating titanium increases formability, reduces springback, takes advantage of a lesser variation in yield strength, and allows for maximum deformation with minimum annealing between forming operations. Severe forming must be done in hot dies, generally with preheated stock. Figure 6 shows the removal of a set of curved channels after being hot formed from a flat sheet. The flat sheet is located in the die and allowed to heat up to temperature. Pressure is slowly applied, bringing down the matching punch and holding for 10 min under pressure prior to removal. Hot forming is ordinarily done at 730 °C (1350 °F) for Ti-6Al-4V material.

The greatest improvement in the ductility and uniformity of properties for most titanium alloys is at temperatures above 540 °C (1000 °F). At still higher temperatures, some alloys exhibit superplasticity (see the section “Superplastic Forming” in this article). However, contamination is also more severe at the higher temperatures. Above approximately 870 °C (1600 °F), forming should be done in vacuum or under a protective atmosphere, such as argon, to minimize oxidation. When done in air, metal removal is required to remove the oxygen-rich layer that forms on the surface of the titanium.

As indicated in Table 6, most hot forming operations are done at temperatures above 540 °C (1000 °F). For applications in which the utmost in ductility is required, temperatures below 315 to 425 °C (600 to 800 °F) are usually avoided. Alpha-beta alloys should not be formed above the  $\beta$ -transus temperature.

Temperatures generally must be kept below 815 °C (1500 °F) to avoid marked deterioration in mechanical properties. Superplastic forming, however, is performed at 870 to 925 °C (1600 to 1700 °F) for some alloys, such as Ti-6Al-4V. At these temperatures, care must be taken not to exceed the  $\beta$ -transus temperature of Ti-6Al-4V. Heating temperature and time at temperature must be controlled so that the titanium is hot for the shortest time practical and the metal temperature is in the correct range.

Reference 14 gives details about forming and the tolerance that can be expected, as well as some of the strength effects. The equipment used is described in detail. The information was generated in 1968 and reflects much of the technology of the day. Some of the forming tools have been improved, and some have not changed.

Hot sizing is used to correct inaccuracies in shape and dimensions in preformed parts. Hot forming takes a flat blank and forms it to the final shape. Hot sizing uses the creep-forming principle to force irregularly shaped parts to assume

**Table 4 Tool materials and lubricants used for forming titanium alloys**

Operation(s)	Tool materials	Lubricants
<b>Cold forming</b>		
Press forming, drawing, drop hammer forming	Cast zinc die or lead punch with stainless steel caps	Graphite suspension in a suitable solvent
Press-brake forming	4340 steel (36–40 HRC)	Graphite suspension in a suitable solvent
Contour roll forming, three-roll forming	AISI A2 tool steel	SAE 60 oil
Stretch forming	Epoxy-faced cast aluminum, cast zinc, cast bronze	Grease-oil mixtures, wax; 10:1 wax-graphite mixture
<b>Hot forming</b>		
Press forming, drawing, drop hammer forming	High-silicon cast iron, stainless steels, heat-resistant alloys	Graphite suspension, boron nitride
Sizing	Low-carbon steel, high-silicon gray or ductile iron, AISI H13 tool steel, stainless steels, heat-resistant alloys	Graphite suspension, boron nitride
Press-brake forming	AISI H11 or H13 tool steel, heat-resistant alloys	Graphite suspension, boron nitride
Contour roll forming, three-roll forming	AISI H11 or H13 tool steel	Graphite suspension, boron nitride
Stretch forming	Cast ceramics, AISI H11 or H13 tool steel, high-silicon gray iron	Graphite suspension, 10:1 wax-graphite mixture, boron nitride
Superplastic forming	Ceramics, 22–49 stainless steel, 49M heat-resistant steel	Boron nitride

**Table 5 Stress-relief schedule for titanium and titanium alloys**

Alloy	Stress-relief temperature		Time, min
	°C	°F	
Commercially pure titanium (all grades)	480–595	900–1100	15–240
<b>Alpha alloys</b>			
5Al-2.5Sn	540–650	1000–1200	15–360
5Al-2.5Sn (ELI)(a)	540–650	1000–1200	15–360
6Al-2Cb-1Ta-0.8Mo	540–650	1000–1200	15–60
8Al-1Mo-1V	595–760	1100–1400	15–75
11Sn-5Zr-2Al-1Mo	480–540	900–1000	120–480
<b>Alpha-beta alloys</b>			
3Al-2.5V	370–595	700–1100	15–240
6Al-4V	480–650	900–1200	60–240
6Al-4V (ELI)(a)	480–650	900–1200	60–240
6Al-6V-2Sn	480–650	900–1200	60–240
6Al-2Sn-4Zr-2Mo	480–650	900–1200	60–240
5Al-2Sn-2Zr-4Mo-4Cr	480–650	900–1200	60–240
6Al-2Sn-2Zr-2Mo-2Cr-0.25Si	480–650	900–1200	60–240
<b>Metastable beta alloys</b>			
13V-11Cr-3Al	705–730	1300–1350	30–60
3Al-8V-6Cr-4Mo-4Zr	705–760	1300–1400	30–60
15V-3Al-3Cr-3Sn	790–815	1450–1500	30–60
10V-2Fe-3Al	675–705	1250–1300	30–60

(a) ELI, extra-low interstitial. Source: Ref 13

the correct shape against a heated die by the controlled application of horizontal and vertical forces over a period of time. Some buckles and wrinkles can be removed from preformed parts in this way. A combination of creep and compression forming is used when reducing bend radii by hot sizing. The effect of temperature on the properties of the metal may limit the maximum useful temperature. Figure 7 shows the setup for creep forming a B-737 part using a hot ceramic die in a conventional furnace. The die is heated up in the furnace, then rolled out and separated. The blank is placed in the tool, the die is then closed up, and weight is added to the top. The tool and weights are then rolled back into the furnace and held at temperature for a period of time sufficient to allow for the creep forming of the part to contour, prior to rolling the tool out,

removing the formed part, and placing another blank into the tool.

Hot platen presses are commonly used for the hot sizing and forming of titanium. The tooling is designed for holding the workpiece to the required shape for the necessary time at temperature. Hot forming/sizing in hot platen presses is done in the following sequence of operations:

- Parts are usually cleaned and coated with a scale inhibitor.
- Parts are loaded on hot forming tools, the press closed, and the parts allowed to heat up prior to applying the forming force.
- Force is applied through the platens and auxiliary side rams as required and held to complete the forming/annealing cycle.

- Parts are removed and cooled in a uniform manner. Hot parts are very susceptible to handling distortion.

Some hot forming temperatures are high enough to age a titanium alloy. Heat-treatable  $\alpha$ - $\beta$  alloys generally must be resolution heat treated after hot forming. Some of the metastable  $\beta$  alloys have solution temperatures in the hot forming range and can be resolution heat treated during the hot forming operation. Solution heat treating thin-gage alloys that require water quench is risky because of distortion.

Hot forming has the advantage of improved uniformity in yield strength, especially when the forming or sizing temperature is above 540 °C (1000 °F). However, care must be taken to limit the accumulation of dimensional errors resulting from:

- Differences in thermal expansion
- Variations in temperature
- Dimensional changes from scale formation
- Changes in dimensions of tools
- Reduction in thickness from chemical pickling operations

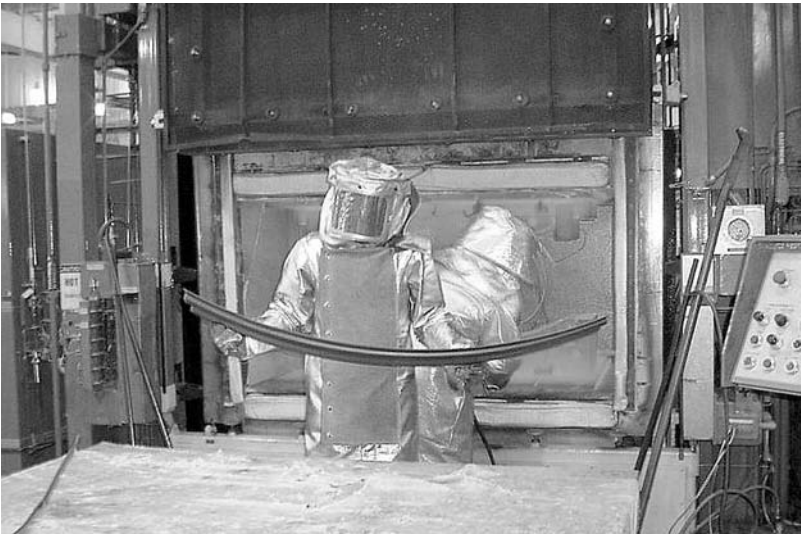


Fig. 6 Hot-formed parts being removed from a hot press

Table 6 Temperatures for the hot forming and annealing of titanium alloys

Material	Annealing/forming temperature		Soak time, min
	°C	°F	
Commercially pure titanium			
All grades	650–815	1200–1500	15–120
Alpha alloys			
5Al-2.5Sn	705–845	1300–1550	10–120
5Al-2.5Sn (ELI)(a)	705–900	1300–1650	10–120
6Al-2Cb-1Ta-0.8Mo	790–900	1450–1650	30–120
8Al-1Mo-1V	760–815	1400–1500	60–480
Alpha-beta alloys			
3Al-2.5V	650–790	1200–1450	30–120
6Al-4V	705–870	1300–1600	15–60
6Al-4V (ELI)(a)	705–870	1300–1600	15–60
6Al-6V-2Sn	705–815	1300–1500	10–120
6Al-2Sn-4Zr-2Mo	870–925	1600–1700	10–60
6Al-2Sn-2Zr-2Cr-2Mo	690–870	1275–1600	15–360
Metastable beta alloys			
13V-11Cr-3Al	760–815	1400–1500	10–60
3Al-8V-6Cr-4Mo-4Zr	760–925	1400–1700	10–60
15V-3Al-3Cr-3Sn	760–815	1400–1500	3–30

(a) ELI, extra-low interstitial. Source: Ref 13

(a) ELI, extra-low interstitial. Source: Ref 13

### Superplastic Forming

The superplastic forming of titanium is currently being used to fabricate a number of sheet metal components for a range of aircraft and aerospace systems. Hundreds of parts are in production, and significant cost savings are being realized through the use of superplastic forming. Additional advantages of superplastic forming over other forming processes include the following:

- Very complex part configurations are readily formed.
- Lighter, more efficient structures are possible.
- It is performed in a single operation, reducing fabrication labor time.
- Depending on part size, more than one piece can be produced per machine cycle.
- The force needed for forming is supplied by a gas, resulting in the application of equal amounts of pressure to all areas of the work-piece.

Superplastic forming is similar to vacuum forming of plastics. A computer system is used to control the gas pressure so that the part forms into the cavity at a constant strain rate. The Ti-6Al-4V material is generally used for this process; however, there are other alloys that work. The material needs to have fine, equiaxed grains and high elongation at the elevated temperature.

The superplastic forming process puts the part on top of a cavity die, as shown in Fig. 8(a). With the tool and blank heated up to forming temperatures in the superplastic range, gas pressure is applied at a predetermined rate to keep a constant strain rate. As the part is formed down into smaller features, the pressure is increased to maintain the strain rate, and the thickness

decreases. The resultant process produces a part that has thinned out based on the geometry of the die (Fig. 8b). There are variations to this process to improve thickness distributions in die design and how the parts are formed.

Figure 9 shows a part blank being loaded onto a hot die in a shuttle press. The lower platen shuttles out on a track to make loading and unloading much easier. The operators wear reflective suits to protect them from the thermal exposure. The tool only needs to reflect one side of the part, whereas, in hot sizing the tool matches both sides of the part.

The limitations of the process include:

- Heat-resistant tool materials are required.
- Equipment that can provide high temperatures and tonnage to balance forming pressures is necessary.
- Long preheat times are necessary to reach the forming temperature.
- A protective atmosphere, such as argon, is helpful.

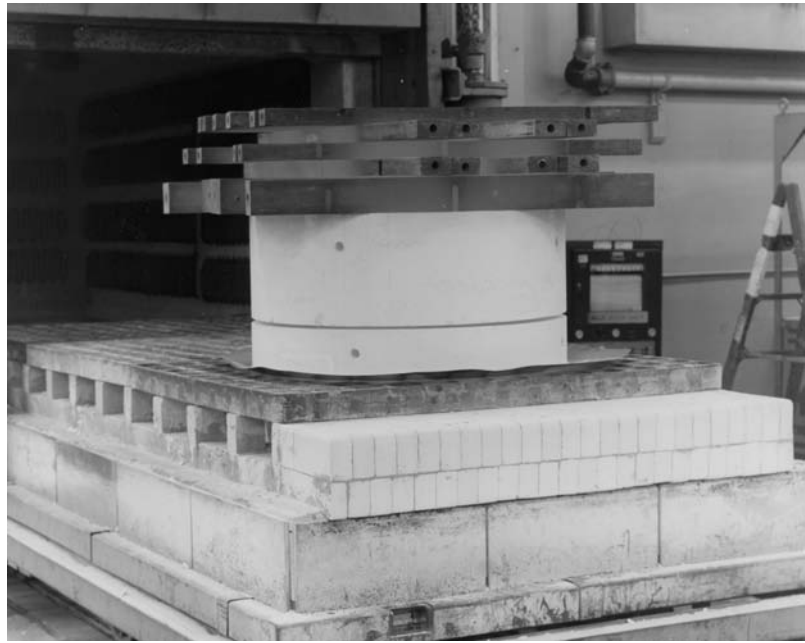
Several forming processes are used in the superplastic forming of titanium alloys. Among these are blow forming, vacuum forming, thermoforming, deep drawing, and superplastic forming/diffusion bonding (see the section “Superplastic Forming/Diffusion Bonding” in this article). All of these processes are discussed in more detail in the article “Superplastic Sheet Forming” in this Volume.

## Superplastic Forming/Diffusion Bonding

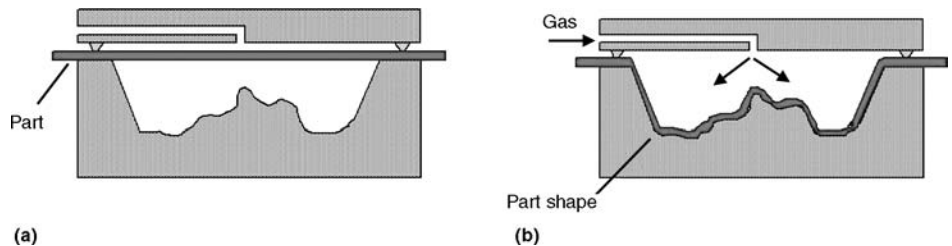
The superplastic forming process can be enhanced with diffusion bonding (solid-state joining). Both processes require similar conditions, such as heat, pressure, clean surfaces, and an inert environment. The combined process is referred to as superplastic forming/diffusion bonding (SPF/DB). Diffusion bonding can be carried out as the first part of the superplastic forming cycle, thus eliminating the need for welding or brazing for complex parts.

The SPF/DB process has greatly extended the applicability of superplastic forming. Using SPF/DB, a sheet can be diffusion bonded and formed onto preplaced details, or two or more sheets can be bonded and formed at selected locations. Figure 10 illustrates the SPF/DB process for three-sheet parts.

Diffusion bonding can be applied only to selected areas of a part by using a stop-off material (Fig. 10 step 1, and Fig. 11) that is placed between the sheets at locations where no bonding is desired. Suitable stop-off materials depend on the alloy being bonded and the temperatures employed; yttria and boron nitride have been successfully used. The powder is mixed and applied to the part in selected areas using the silk screening process (Fig. 11). Figure 10, step 2 shows the sheets sealed into an airtight pack. In step 3, the pack is bonded



**Fig. 7** Creep forming a part for the B-737 in a ceramic die using a conventional furnace. The titanium is pushed into the correct shape through the application of heat, weight, and time.



**Fig. 8** Superplastic forming of titanium. (a) Setup at the start of the forming cycle. (b) After forming is completed



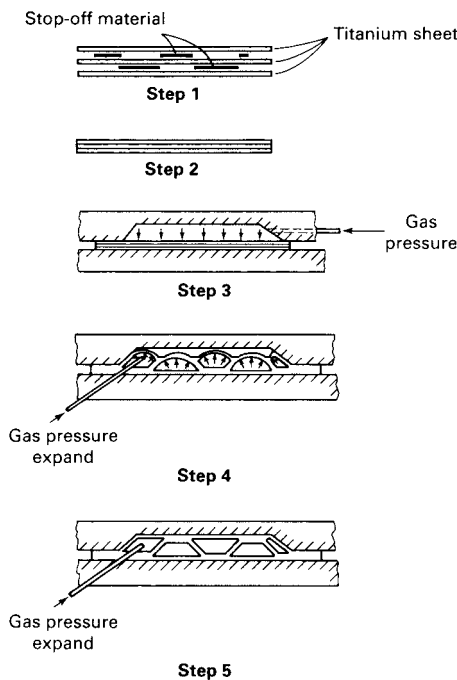
**Fig. 9** Loading a sheet of titanium into a superplastic forming die



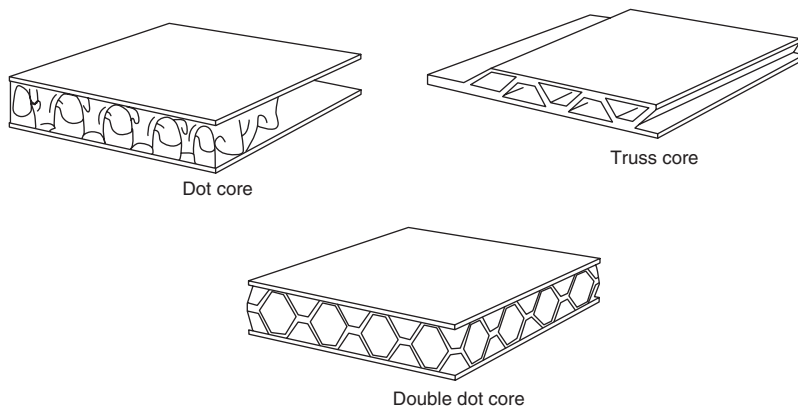
together under pressure and temperature. In step 4, the pack is inflated to start forming areas where the stop-off material was applied. Step 5 completes the forming cycle, fully forming the part prior to removal.

Diffusion bonding in combination with superplastic forming can produce lightweight panel structures, as shown in Fig. 12.

Superplastic forming and SPF/DB are gaining acceptance in the aircraft/aerospace industry. Figure 13 shows the increase in applications for superplastically formed titanium parts in four military aircraft since 1980; applications for commercial aircraft and in the aerospace industry also are increasing. Inspection of the bond is usually done with ultrasonic inspection methods.



**Fig. 10** Schematic showing the sequence of operations for superplastic forming/diffusion bonding of three-sheet titanium parts



**Fig. 12** Typical lightweight panels produced with diffusion bonding and superplastic forming

Mechanical analysis of the joint and bond is based on part configuration.

Applications range from simple clips and brackets to airframe components and other load-bearing structures. Figures 14 and 15 show current applications for superplastically formed parts and illustrate the cost and weight savings that can be realized by using superplastic forming. Reducing the part count and assembly costs and making a more structurally efficient part result in cost and weight savings.

## Press-Brake Forming

Titanium alloys cold formed in a press brake behave like work-hardened stainless steel, except that springback is considerably greater (see the article "Forming of Stainless Steel" in this Volume). If bend radii are large enough, forming can be done cold. However, if bend radii are small enough to cause cracking in cold forming, either hot forming or the process of cold forming followed by hot sizing must be used.

The setup and tooling for press-brake air bending are relatively simple because the ram stroke determines the bend angle. The only tooling adjustments are the span width of the die and the radii of the punch. The span width of the



**Fig. 11** Typical silk screen application of the stop-off material

die affects the formability of bend specimens and is determined by the punch radius and the work metal thickness, as shown in Fig. 16. Acceptable conditions for dies in press-brake forming are shown as the shaded area between the upper and lower limits in Fig. 16.

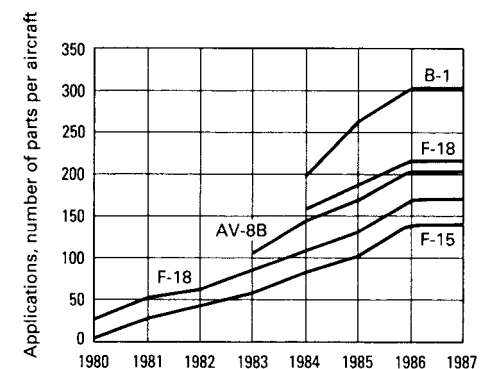
The minimum bend radius obtainable in press-brake forming depends on the alloy, work metal thickness, and forming temperature (Table 7). Springback in press-brake forming depends on the ratio of punch radius (bend radius) to stock thickness and on forming temperature, as shown in Fig. 17 for alloy Ti-6Al-4V (Fig. 17 is not to be used for minimum bend radii).

Hot-brake forming puts linear bends in a sheet by heating up the blank, then forming in a cold press brake. When this technique is used, a stress relief follows because the forming takes place quicker than the stress-relief time required to prevent springback of the part. Springback appears to be approximately the same with the blank heated as with a cold blank when the forming takes place very quickly. This process appears to work well when the bend radii is three times the thickness or larger in Ti-6Al-4V material. It is difficult to determine the temperature at which the forming takes place.

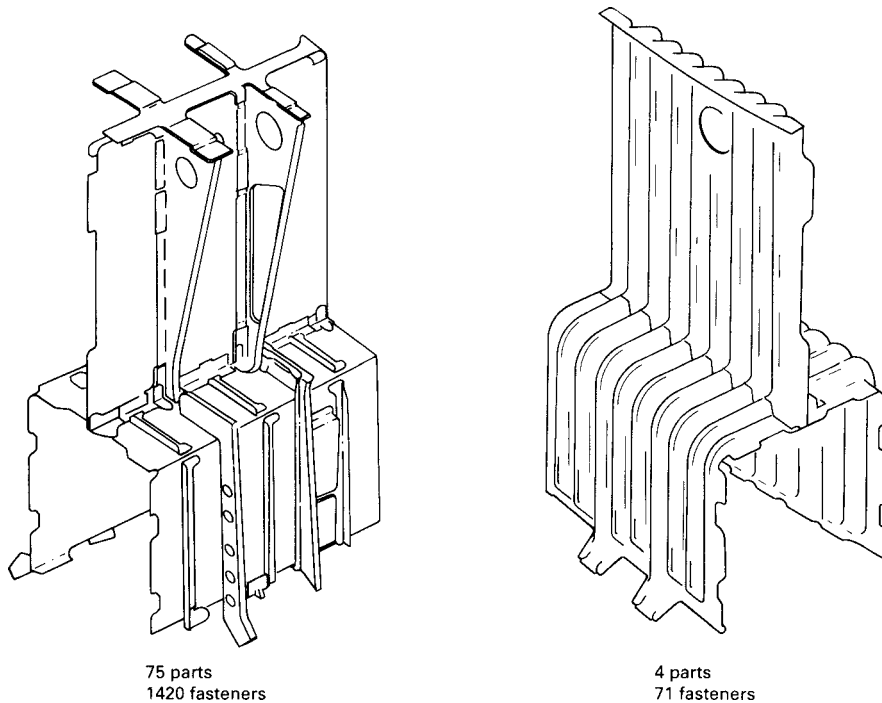
The deep drawing of titanium alloys is limited to the more formable alloys, such as CP titanium in the lower-strength grades. Superplastic forming can also be used for deep drawing; however, a draft angle is usually required because it is difficult to remove parts from a shape that has vertical sides, unless there is a guided removal system that keeps the part aligned.

However, general guidelines for the deep drawing of titanium alloy into dome shapes at room temperature are:

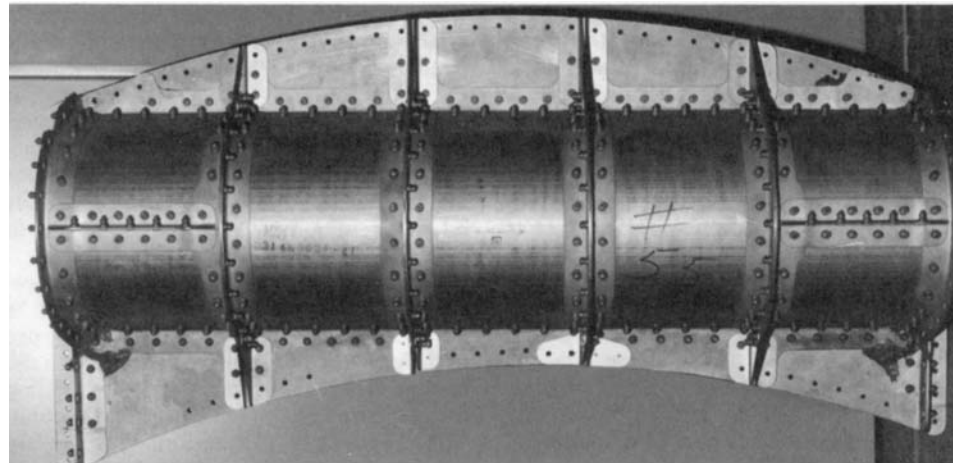
- The edges and surface of the blank should be smooth to prevent cracking during forming.
- The flange radius should be at least 9.5 to 12.7 mm (0.375 to 0.500 in.).
- The workpiece should be clean before each forming operation.
- An overlay or pressure cap can be used to prevent wrinkles.



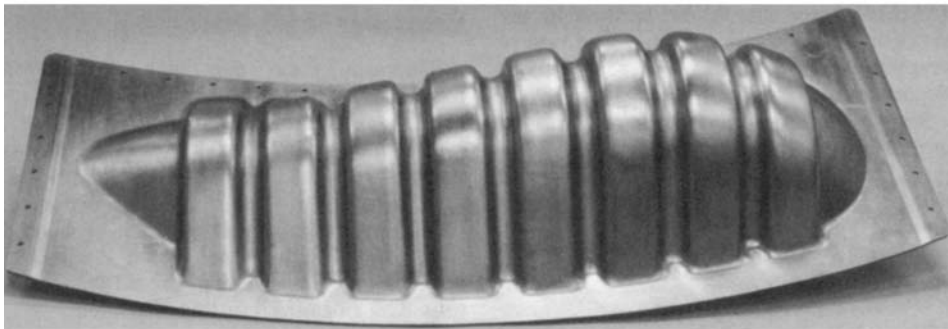
**Fig. 13** Applications of superplastically formed titanium parts in military aircraft. Source: Ref 15



**Fig. 14** Original keel design (left) and superplastically formed titanium keel section (right) for F-15 fighter aircraft. The change to the superplastically formed part resulted in a 58% cost savings and a 31% weight savings. Source: Ref 15



(a)



(b)

**Fig. 15** Ti-6Al-4V engine nacelle component for the Boeing 757 aircraft. (a) Part as previously fabricated required 41 detail parts and more than 200 fasteners. (b) Superplastically formed part is formed from a single sheet.

- Severe forming and localized deformation should be avoided; forming pressure should be applied slowly.
- The punch should be polished to prevent galling, regardless of lubrication. Often, it is preferred to weld a layer of hard bronze on top of more conventional tooling steels to minimize galling and damage to the part, the tool, or both.

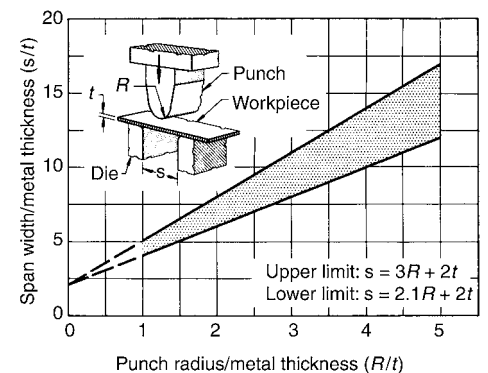
The deep drawing of dome and hemisphere shapes has also been accomplished at room temperature in a rubber-diaphragm press. A detailed description of rubber-diaphragm forming is available in the article "Rubber-Pad Forming and Hydroforming" in this Volume. Deep drawing is discussed in more detail in the article "Deep Drawing" in this Volume.

**Hot Drawing.** At temperatures of approximately 675 °C (1250 °F), titanium can be drawn deeper, with more difficult forming than at room temperature. Generally, depth of draw depends on material, workpiece shape, required radii, forming temperature, die design, die material, and lubricant. The setup becomes more critical than in hot sizing because the sides become more vertical. A setup that resembles a cold forming die works best to maintain alignment of the tools, and the tool is only heated where it contacts the part. Normal hot sizing presses usually have distorted heated platens that make alignment difficult when making vertical draws.

## Power (Shear) Spinning

Most titanium alloys are difficult to form by power spinning. Alloys Ti-6Al-4V and some grades of CP titanium are the most responsive to forming by this method.

Most tools for the power spinning of titanium are made of high-speed steel and hardened to 60 HRC. Mandrels are heated for hot spinning, though. It may be advantageous to heat the workpiece also. Tube preforms can be heated by radiation. The hot power spinning of titanium is done at 205 to 980 °C (400 to 1800 °F), depending on the alloy and the operation.



**Fig. 16** Optimal relationships among span width of die, punch radius, and work metal thickness in the press-brake forming of titanium alloys. Shaded area indicates acceptable forming limits.

**Lubricants** for the power spinning of titanium depend on the forming temperature used. At temperatures up to 205 °C (400 °F), heavy drawing oils, graphite-containing greases, and colloidal graphite are used. Colloidal graphite and molybdenum disulfide are employed at temperatures to 425 °C (800 °F); above this temperature, colloidal graphite, powdered mica, and boron nitride are used. More information on power spinning is available in the article “Spinning” in this Volume.

Rubber-Pad Forming

The cold forming of titanium in a press with tooling that includes a rubber pad is used mostly for flanging thin stock and for forming beads and shallow recesses. The capacity of the press controls the range in size, strength, and thickness of blanks that can be formed. Within this range, however, additional limits may be set by buckling and splitting. Auxiliary devices, such as overlays, wiper rings, and sandwiches, are usually needed in rubber-pad forming to improve the forming and to reduce the amount of wrinkling and buckling. Rubber-pad forming is generally done at room temperature or with only moderate heat. Forming is almost always followed by hot sizing to remove springback, to sharpen radii, to smooth out wrinkles and

buckles, to stress relieve, and to complete the forming. Handwork is sometimes needed to complete the forming.

Sharp bends can be made at higher forming pressures. Figure 18 shows the effect of pad pressure on bend radius for two titanium alloys.

Springback behavior of titanium and its alloys in rubber-pad forming differs somewhat from that observed in other methods of forming. In general, springback in forming titanium varies directly with the ratio of bend radius to work metal thickness, and inversely with forming temperature. Springback is also inversely proportional to forming pressure.

Beads can be formed to a limited extent in titanium alloy sheet by rubber-pad forming. However, beads are readily formed by superplastic forming, and this process is preferred. Additional information on rubber-pad forming is available in the article “Rubber-Pad Forming and Hydroforming” in this Volume.

Stretch Forming

Tooling that is used for the stretch forming of stainless steel is generally suitable for the cold stretch forming of titanium, when used with a high clamping force that will prevent slipping and tearing. Particular attention should be paid to the tooth or serration pattern for the jaws to preclude slipping and/or breaking. Titanium may exhibit irregular incremental stretch under tension loads; therefore, optimal results are obtained when titanium is stretch formed at slow strain

rates. The rate of wrapping around a die should be no more than 205 mm/min (8 in./min). Post-stretching of Ti-6Al-4V material does not work well because it is very notch sensitive and may break. Lower-strength CP titanium stretch forms well. In general, material preparation is critical for cold stretching of titanium alloys due to the notch sensitivity.

In the stretch forming of angles, channels, and hat-shaped sections, deformation occurs mainly by bending at the fulcrum point of the die surface; compression buckling is avoided by applying enough tensile load to produce approximately 1% elongation in the inner fibers. The outer fibers elongate more; the extent depends on the curvature of the die and on the shape of the workpiece. It is sometimes preferable or required (especially if sufficient forming power is not available) to stretch wrap at elevated temperature. Again, the wrapping speed must be slow to prevent local overheating or necking.

Formability limits can be extended by permitting small compression buckles to occur at the inner fibers and removing them later by hot sizing. The buckled region represents a condition of overforming and should be limited to the amount that can be effectively removed by hot sizing. Care must be taken to only permit buckling that can be removed. Small, sharp wrinkles may indent the hot sizing tool rather than be removed.

Compression buckling is not a problem when sheet is stretch formed to produce single or compound curves. The ductility of sheet varies with orientation and is generally better when the direction of rolling concedes with the direction of stretching. In the stretch forming of compound curves, the stretching force should be applied in the direction of the smaller radius. The rate of wrapping around the die should be no more than 205 mm/min (8 in./min).

Stretch forming is being replaced in many applications by superplastic forming. Additional information on the stretch forming process is available in the article “Stretch Forming” in this Volume.

Table 7 Minimum bend radii obtainable in the cold press-brake bending of annealed or solution-treated titanium alloys

Alloy	Minimum bend radius as a function of sheet thickness, <i>t</i>	
	<i>t</i> < 1.75 mm (0.069 in.)	1.75 mm (0.069 in.) < <i>t</i> < 4.76 mm (0.1875 in.)
<b>Commercially pure titanium</b>		
ASTM grade 1	2.5	3.0
ASTM grade 2	2.0	2.5
ASTM grade 3	2.0	2.5
ASTM grade 4	1.5	2.0
<b>α alloys</b>		
Ti-5Al-2.5Sn	4.0	4.5
Ti-5Al-2.5Sn ELI	4.0	4.5
Ti-6Al-2Nb-1Ta-0.8Mo	...	...
Ti-8Al-1Mo-1V	4.5(a)	5.0(b)
<b>α-β alloys</b>		
Ti-6Al-4V	4.5	5.0
Ti-6Al-4V ELI	4.5	5.0
Ti-6Al-6V-2Sn	4.0	4.5
Ti-6Al-2Sn-4Zr-2Mo	4.5	5.0
Ti-3Al-2.5V	2.5	3.0
Ti-8Mn	6.0	7.0
<b>β alloys</b>		
Ti-13V-11Cr-3Al	3.0	3.5
Ti-11.5Mo-6Zr-4.5Sn	3.0	3.0
Ti-3Al-8V-6Cr-4Mo-4Zr	3.5	4.0
Ti-8Mo-8V-2Fe-3Al	3.5	3.5
Ti-15V-3Cr-3Sn-3Al(c)	2.0	2.0

ELI, extra-low interstitial. Source: Ref 16, (a) 4.0 in transverse direction, (b) 4.5 in transverse direction, (c) Source: Ref 17

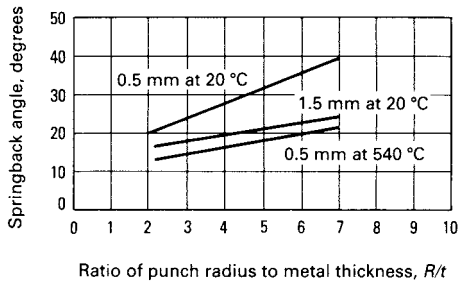


Fig. 17 Effect of ratio of punch radius to work metal thickness on springback in the press-brake bending of Ti-6Al-4V at two temperatures

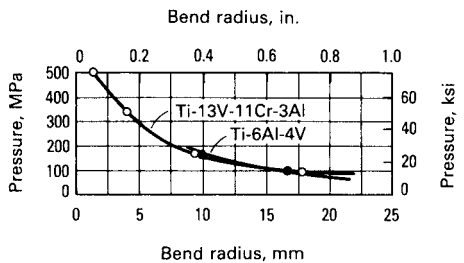


Fig. 18 Effect of pad pressure on radii formed in 1.60 mm (0.063 in.) thick titanium alloy sheets at room temperature

Contour Roll Forming

Titanium sheet can be contour roll formed like any other sheet metal, but with special consideration for allowable bend radius and for the greater springback that is characteristic of titanium. Springback is affected to some extent by roll pressure. Often, hot rolling must be done on heated work metal with heated rolls. Additional information is available in the article “Contour Roll Forming” in this Volume.

Roll forming is an economical method of forming titanium alloy sheet into aircraft skins, cylinders, or parts of cylinders. The sheet should be flat within 0.15 mm (0.006 in.) for each 51 mm (2 in.) of length. The corners of the sheet should be chamfered to prevent marking of the rolls.

The upper roll of the three-roll assembly can be adjusted vertically. The radius of the bend is controlled by the roll adjustment. Premature failure will occur if the contour radius is decreased too rapidly; however, too many passes through the rolls may cause excessive work hardening of the work metal. Several trial parts must sometimes be made in a new material or shape to establish suitable operating conditions.

Three-roll forming is also used to form curves in channels that have flanges of 38 mm (1.5 in.) or less. Figure 19 shows the use of the process for curving a channel with the heel in. Transverse buckling and wrinkling are common failures in the forming of channels. The article "Three-Roll Forming" in this Volume contains more information on this process.

## Creep Forming

In creep forming, heat and pressure are combined to cause the slow forming of titanium sheet into various shapes, such as double-curve panels, channel sections, Z-sections, large rings, and small joggles. The metal flows plastically at a stress below its yield strength. At low temperature, creep rates are ordinarily very low (for example, 0.1% elongation in 1000 h), but the creep rate of titanium accelerates sharply with increasing temperature.

Creep forming/hot straightening is done by applying a force on the part over a period of time while the part is at temperature. The desired effect is to force the part into the correct configuration while stress relieving. This will ensure that the part stays in the correct configuration when cooled down. Methods may include the following:

- A blank is clamped at the edges, as for stretch forming, and a heated male tool is loaded to press against the unsupported portion of the blank; the metal yields under the combination of heat and pressure and slowly creeps to fit the tool.
- The part is located on a tool with weights and run through a stress-relief cycle. During this cycle, the part will deform into the correct configuration.
- The part is forced into the correct configuration, then a stress-relief cycle is run.

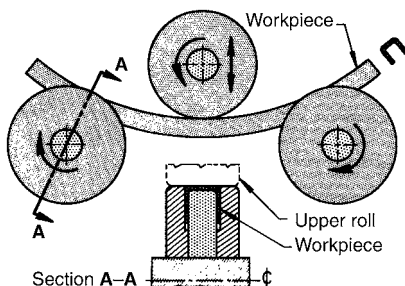


Fig. 19 Use of three-roll forming to produce a curve in a U-section channel

- A heated die and vacuum bag is used. The blank is placed in the tool under heat and a vacuum is applied to produce the necessary forming force, then the part is run through a stress-relief cycle. Additional time and/or pressure may be required to obtain the desired contour.

Temperatures for creep forming are the same as those used in hot forming (Table 6). Generally, titanium must be held at the creep-forming temperature for 3 to 20 min per operation; creep forming sometimes takes as long as 2 h.

## Vacuum Forming

Large panels (some as much as 18 m, or 60 ft, long) for aircraft are sometimes vacuum formed from titanium alloy sheet. Vacuum forming, however, can be by superplastic forming for smaller panels. There are some advantages to developing stand-alone vacuum forming tools, because they tend to be simpler to maintain and do not require a large press to create the forces. For vacuum forming, the blank is laid on a die of heated concrete, ceramic, or metal, and a somewhat larger flexible diaphragm is laid on top of the blank to provide a seal around its edges. Usually, insulation is placed between the part and the flexible diaphragm. This helps to hold in the heat as well as keep the heat off the diaphragm. It should be noted that the water needs to be removed from concrete and ceramic material through a proper curing cycle prior to heating, or it will come out in a most unsatisfactory way. Ceramic material is normally preferred because it has a very low coefficient of expansion and does not flake off under a temperature gradient. After the blank has been heated to forming

temperature, the air is pumped out from between the blank and the die so that atmospheric pressure is used to form the work. This method, a kind of creep forming, cannot bend the work to sharp radii. Finite element analysis, similar to that done for superplastic forming, can be used to determine forming capabilities at a given pressure, temperature, and time.

## Drop Hammer Forming

Forming of titanium using drop hammers is becoming a lost art and perhaps the method of last resort. The tooling is quick, and the method does provide a preform. Hot sizing is required to obtain the desired contour. As shown in Fig. 20, a heat source is normally used to preheat the blank prior to forming. The alloys used in hammer tools contain lead, zinc, and other low-melting metals that contaminate titanium. These need to be removed from the titanium prior to heating. This can be done in a couple of ways. One is to not permit lead, zinc, or other low-melting metals that contaminate titanium to come in contact with the titanium. To do this, the drop hammer tools can be capped with sheet steel, stainless steel, or nickel alloy, depending on the expected tool life. Nickel-base alloys, in thicknesses of 0.635 to 0.813 mm (0.025 to 0.032 in.), have the longest life. The other way is to chemically remove the contamination from the titanium prior to reheating.

As indicated in Table 6, severe forming of most titanium alloys, which includes drop hammer forming, is done at approximately 500 to 800 °C (900 to 1500 °F). Thermal expansion of the dies must be considered in the design. The approximate rate of expansion for steel dies is 0.006 mm/mm (0.006 in./in.). The expansion



Fig. 20 Drop hammer forming showing oven next to the drop hammer

rate will be different for different alloys and temperatures.

Multistage tools can be used if the part shape is complex and cannot be formed in one blow. The minimum thickness of titanium sheet for drop hammer forming is 0.635 mm (0.025 in.); thicker sheet is used for complex shapes. Minimum thickness is determined from a number of variables. Contour will cause buckling in the thinner gages. Surface damage seems to occur more on the thinner gages. Total tolerance on parts formed in drop hammers is usually 1.6 mm (0.06 in.). Typically, hammer forming is used as a preform to hot sizing. More information on the drop hammer forming process is available in the article “Drop Hammer Forming” in this Volume.

Joggling

Joggling is frequently done on titanium alloy sheet. A joggle is an offset in a flat plane, consisting of two parallel bends in opposite directions at the same angle (Fig. 21). Generally, the joggle angle is less than 45°.

Depending on joggle depth, joggles can be either formed completely at room temperature or at elevated temperature in press brakes and mechanical or hydraulic presses. Room-temperature joggle limits are given in Table 8. The practice is to preform at room temperature and then hot size (“set” the joggle) in a heated die. The sizing operation is usually done under conditions that result in stress relieving or aging.

Joggles with radii smaller than the minimum bend radii (Table 7) at room temperature, or joggles with length-to-depth ratios of less than approximately 6 to 1, are more successfully formed at elevated temperature. Forming temperature varies between 315 and 650 °C (600 and 1200 °F), depending on the alloy and its heat treated condition. Annealed alloys are joggled at 315 to 425 °C (600 to 800 °F). Heat treated or partly heat treated alloys are joggled at, or near, their aging temperature.

Dimpling

Dimpling produces a small conical flange around a hole in sheet metal parts that are to be assembled with flush or flathead fasteners. Dimpling is most commonly applied to sheets that are too thin for countersinking. Sheets are

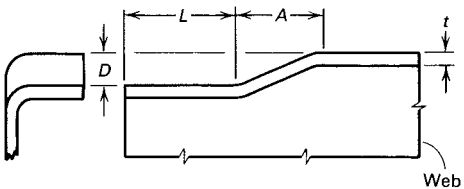


Fig. 21 Details of a joggle. See Table 8 for room-temperature joggle limits of several titanium alloys. *t*, sheet thickness; *D*, joggle height; *L*, joggle length; *A*, joggle allowance. Source: Ref 18

always dimpled in the condition in which they are to be used, because subsequent heat treatment may cause distortion of the holes or dimensional changes in the sheet.

The hot ram-coin dimpling process is generally used. In hot ram-coin dimpling, force in excess of that required for forming is applied to coin the dimpled area and to reduce the amount of springback.

Titanium is dimpled at up to 650 °C (1200 °F) with tool steel dies. If higher temperatures are required, heat-resistant alloy or ceramic tooling is needed in order to prevent deformation of the dies during dimpling. The work metal is usually heated by conduction from the dimpling tools, which are automated to complete the dimpling stroke at a predetermined temperature.

Pilot holes must be drilled, rather than punched, and must be smooth, round, cylindrical, and free of burrs. Because of the notch sensitivity of titanium, care must be taken in deburring the holes.

The amount of stretch required to form a dimple varies with the head and body diameters of the fastener and the bend angle. If the metal is not ductile enough to withstand forming to the

required shape, cracks will occur radially in the edge of the stretch flange, or circumferentially at the bend radius. Circumferential cracks are more common in thin sheet; radial cracks are more common in thick stock.

Explosive Forming

Within the limits set by its mechanical properties, titanium can be explosive formed like other metals. Explosive forming is most commonly used for cladding titanium to other metals. Titanium is explosive formed using techniques similar to those used for other metals and alloys (see the article “High-Velocity Metal Forming” in this Volume).

Bending of Tubing

Round tubing of CP titanium and alloy Ti-3Al-2.5V can be formed at room temperature in ordinary draw bending machines. When hot bending is required, the equipment is modified

Table 8 Room-temperature joggle limits for several annealed titanium alloys

See Fig. 21 for definitions of joggle dimensions given here, and Table 7 for minimum bend radii.

Alloy	Sheet thickness, <i>t</i>		<i>A</i> , minimum	<i>D</i> , maximum	<i>L</i> , minimum
	mm	in.			
Commercially pure titanium(a)	Up to 4.75	Up to 0.187	6 <i>D</i>	3 <i>t</i>	5 <i>D</i>
Commercially pure titanium(b)	Up to 4.75	Up to 0.187	4 <i>D</i>	4 <i>t</i>	5 <i>D</i>
Ti-8Al-1Mo-1V	Up to 2.29	Up to 0.090	8 <i>D</i>	2.5 <i>t</i>	6 <i>D</i>
Ti-6Al-4V	Up to 2.29	Up to 0.090	8 <i>D</i>	2.5 <i>t</i>	6 <i>D</i>
Ti-6Al-6V-2Sn	Up to 2.29	Up to 0.090	8 <i>D</i>	2 <i>t</i>	6 <i>D</i>
Ti-5Al-2.5Sn	Up to 3.18	Up to 0.125	6 <i>D</i>	3 <i>t</i>	6 <i>D</i>
Ti-13V-11Cr-3Al	Up to 4.75	Up to 0.187	6 <i>D</i>	3 <i>t</i>	6 <i>D</i>
Ti-15V-3Cr-3Sn-3Al	Up to 2.29	Up to 0.090	4 <i>D</i>	4 <i>t</i>	5 <i>D</i>

(a) Minimum yield strength: 483 MPa (70 ksi). (b) Minimum yield strength: <483 MPa (70 ksi). Source: Ref 18

Table 9 Limits on radii and angles in bending of commercially pure titanium

						Bending conditions			
						Maximum angle(a), degrees	Preferred minimum bend radius		Preferred maximum angle(a), degrees
Tube outside diameter		Wall thickness		Minimum bend radius			mm	in.	
mm	in.	mm	in.	mm	in.				
Room-temperature bending									
38.1	1.5	0.41	0.016	57.2	2.25	90	75	3	120
		0.51	0.020	57.2	2.25	100	75	3	160
50.8	2.0	0.41	0.016	76.2	3.00	80	100	4	110
		0.51	0.020	76.2	3.00	100	100	4	150
63.5	2.5	0.41	0.016	95.3	3.75	70	127	5	100
		0.89	0.035	95.3	3.75	110	127	5	180
Elevated-temperature bending (175 to 205 °C, or 350 to 400 °F)									
76.2	3.0	0.41	0.016	114.3	4.50	90	150	6	120
		0.89	0.035	114.3	4.50	130	150	6	180
88.9	3.5	0.41	0.016	133.4	5.25	90	178	7	120
		0.89	0.035	133.4	5.25	130	178	7	180
101.6	4.0	0.41	0.016	152.4	6.00	110	203	8	160
		0.89	0.035	152.4	6.00	120	203	8	180
114.3	4.5	0.41	0.016	171.5	6.75	130	229	9	140
		0.89	0.035	171.5	6.75	140	229	9	140
127.0	5.0	0.51	0.020	254.0	10.00	...	254	10	110
152.4	6.0	0.51	0.020	304.8	12.00	...	305	12	100

(a) Maximum bend angles are based on the use of a clamp section three times as long as the diameter of the tubing and on maximum mandrel-ball support of the tubing.

by adding heat to the tools. Minimum and preferred conditions for bending tubing of CP titanium at room temperature and at elevated temperatures are given in Table 9. As indicated in the table, tubing up to 63.5 mm (2.5 in.) in diameter ordinarily is bent at room temperature, while larger sizes are bent at temperatures of 175 to 205 °C (350 to 400 °F). In either case, bend radius is limited chiefly by tubing diameter, but maximum bend angle is affected by both diameter and wall thickness.

Commercially pure titanium deforms locally if tension is not applied evenly. Bending should be slow; rates of  $1/4^\circ$  to  $4^\circ$  per minute are suitable. A lubricant should be used.

Tools used in bending titanium and titanium alloy tubing are shown in Fig. 22. In this type of apparatus, the tubing is gripped between the clamp and the straight portion of the rotating form block tightly enough to prevent axial slip-

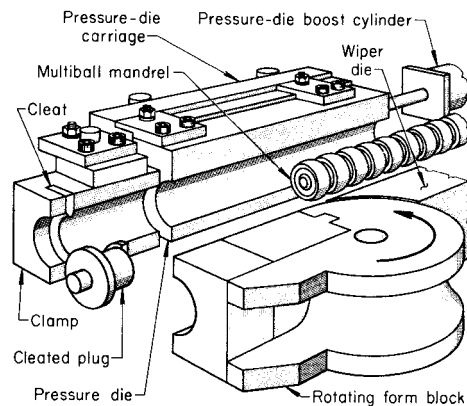
ping during bending. The clamped end of the tubing is supported by a plug. The cleat insert in the clamp and that attached to the end of the plug (Fig. 22) are used only in bending the larger sizes of tubing that have thin walls, for which greater gripping power is needed.

Computers are also being applied to titanium tube bending, especially at large aircraft and aerospace companies. Computer measurement systems are used during bending, and software packages are available that can design bend geometries. Completely automated precision bending can be performed using computers and numerically controlled bending equipment. More information on automated tube bending is available in the article "Bending and Forming of Tubing" in this Volume.

Drawing oils are used as lubricants for forming CP titanium tubing at room temperature. Grease with graphite is used as a lubricant for the hot bending of CP titanium tubing but is not recommended for temperatures above 315 °C (600 °F). Phosphate conversion coatings are sometimes used for hot bending of titanium tubing.

Force Wright Aeronautical Laboratories, Sept 1980

7. J.A. Wert and N.E. Paton, *Metall. Trans. A*, Vol 14, 1983, p 2535
8. C.H. Hamilton and L.F. Nevarez, Rockwell International Science Center, unpublished research
9. F. Dymant, Self and Solute Diffusion in Titanium and Titanium Alloys, *Titanium '80: Science and Technology*, Vol 1, H. Kimura and O. Izumi, Ed., The Metallurgical Society, 1980, p 519
10. N.E.W. DeReca and C.M. Libanat, *Acta Metall.*, Vol 16, 1968, p 1297
11. A. Pontau and D. Lazarus, *Phys. Rev. B*, Vol 19, 1979, p 4027
12. E.W. Collings, *The Physical Metallurgy of Titanium Alloys*, American Society for Metals, 1984, p 151
13. Military Standard MIL-H-81200B, U.S. Government Printing Office
14. J.S. Newman and J.S. Caramanica, "Optimum Forming Processes and Equipment Necessary to Produce High Quality, Close Tolerance Titanium Alloy Parts," AFMR-TR-68-257, final technical report, 1968
15. J.R. Williamson, *Superplastic Forming/Diffusion Bonding of Titanium: An Air Force Overview*, Air Force Wright Aeronautical Laboratories, 1986
16. Military Standard MIL-T-9046J, U.S. Government Printing Office
17. G.A. Lenning, J.A. Hall, M.E. Rosenblum, and W.B. Trepel, "Cold Formable Titanium Sheet Material Ti-15-3-3-3," Report AFWAL-TR-82-4174, Air Force Wright Aeronautical Laboratories, Dec 1982
18. "Fabrication Practices for Titanium and Titanium Alloys," Lockheed Corporate Process Specification LCP70-1099, Revision B, Lockheed-California Company, Oct 1983



**Fig. 22** Tools used for bending titanium tubing. The cleats on the clamp and plug are used only for bending of large-diameter tubing with thin walls. For hot bending, the pressure die and mandrel are integrally heated.

## REFERENCES

1. C.H. Hamilton, Superplasticity in Titanium Alloys, *Superplastic Forming*, S.P. Agrawal, Ed., American Society for Metals, 1985, p 13-22
2. D. Lee and W. Backofen, *Trans. TMS-AIME*, Vol 239, 1967, p 1034
3. A.K. Ghosh and C.H. Hamilton, *Metall. Trans. A*, Vol 10, 1979, p 699
4. N.E. Paton and C.H. Hamilton, *Metall. Trans. A*, Vol 10, 1979, p 241
5. A. Arieli and A. Rosen, *Metall. Trans. A*, Vol 8, 1977, p 1591
6. T.L. Mackay, S.M.L. Sastry, and C.F. Yolton, Report AFWAL-TR-80-4038, Air